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COMMON EXERCISES IN WHOLE BUILDING HAM MODELLING

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ABSTRACT

Subtask 1 of the IEA ECBCS Annex 41 (IEA 2007) project had the purpose to advance development in modelling of integral Heat, Air and Moisture (HAM) transfer processes that take place in "whole buildings". Such modelling considers all relevant elements of buildings: The indoor air, building envelope, inside constructions, furnishing, systems and users. The building elements interact with each other and with the outside climate. Subtask 1 dealt with modelling principles and the arrangement and execution of so-called common exercises with the purpose to gauge how well it was possible to succeed in such modelling. The paper gives an overview of the Common Exercises which have been carried out in the Subtask.

INTRODUCTION

Indoor air humidity is an important factor influencing air quality, energy consumption of buildings and the durability of building materials. Indoor air moisture depends on several factors, such as moisture sources (human presence and activity, equipment), airflow, sorption from/to solid materials and possible condensation. As all these phenomena are strongly interdependent, numerical predictions of indoor air humidity need to be integrated into combined heat-airflow simulation tools.

Subtask 1 of the IEA ECBCS Annex 41 project focused on the modelling of integral Heat, Air and Moisture (HAM) transfer processes that take place in "whole buildings".

COMMON EXERCISES

The purpose of the Common Exercises (CE) was to test the current possibilities to use modelling as a means to predict the integrated hygrothermal behaviour of buildings and to stimulate new development in this area. This could be done either by clever use of already existing models, or by new modelling, where models were developed either from scratch or as extensions to already existing models, which have some of the desired performances.

Another important purpose of the common exercises was to provide a basis for validating existing models and to assess their capacity to simulate complex processes.

The following CEs have been carried out as part of Subtask 1 of Annex 41:

- CE0. Validation of thermal aspects of the employed models.
- CE1. Expanding on CE0 by considering moisture interactions.
- CE2. Experimental climate chamber tests in the laboratory.
- CE3. Double outdoor climatic chamber test.
- CE4. Extension of CE3 with moisture management to reduce energy consumption.
- CE5. Real life row house.
- CE6. Two-story test-hut data determined in Environmental Chamber.

The Common Exercises were developed by different participants of the project. The authors of this paper were leaders of Subtask 1, and also were responsible for developing CE0, CE1 and CE4. Table 1 gives a more specific overview of the topics dealt with in the different exercises. Table 2 shows which simulation codes were used in the different CEs. For detailed comparison of the results and capabilities of different simulation tools see Woloszyn and Rode, 2008.

BESTEST as Common Exercises 0 and 1

Both CE0 and CE1 have analyzed the IEA BESTEST building of IEA SHC Task 12 & ECBCS Annex 21 (Judkoff and Neymark, 1995), see Figure 1. The building is artificial, so no measurement data exist, but the case served as basis for comparison between different modelling results.

CE 0 Thermal building simulation.

For the purpose of Annex 41, four cases were chosen from the original BESTEST procedure. The four cases concerned a building which was either made of lightweight constructions (BESTEST case "600") or heavyweight constructions ("900"), and they were either simulated under free floating thermal conditions or with heating and cooling systems.

Table 1
Overview of the common exercises and their themes

	CE0	CE1	CE2	CE3	CE4	CE5	CE6
Energy	X	X		X	X	X	X
Airflow			X			X	X
Multi-zone						X	X
Moisture buffering			X	X	X	X	X
Moisture transfer		X				X	
Experimental data			X	X		X*	X
Analytical solution		X*				X*	

*Concerns only a part of the exercise

Table 2
Overview of the participating institutions and the used simulation tools

Institution	**Country**	**CE0**	**CE1**	**CE2**	**CE3**	**CE4**
CETHIL	France	Clim2000 TRNSYS	Clim2000	Clim2000 TRNSYS	Clim2000	Clim2000
CON	Canada	-	-	HAMFitPlus	HAMFitPlus	-
CTH	Sweden	HAM-Tools	HAM-Tools	HAM-Tools	HAM-Tools	HAM-Tools
CSTB	France	-	-	HAM-Tools	-	-
DTU	Denmark	BSim	BSim		BSim	-
FhG	Germany	Wufi-Plus	Wufi-Plus		Raummodell Wufi-Plus	-
KIU	Japan	-	Xam	Xam, STREAM		-
KUL	Belgium	TRNSYS ESP-r	-	-	-	-
KYU	Japan	-	Original Code	-	-	-
ORNL	USA	EnergyPlus	EnergyPlus	-	-	-
PUCPR	Brazil	-	PowerDomus 1.0	-	PowerDomus 1.0 TRNSYS	TRNSYS
SAS	Slovakia	-	Esp-r + Wufi + NPI	-	Esp-r + NPI	
TTU	Estonia	IDA ICE	IDA ICE	-	IDA ICE	IDA ICE
TUD	Germany	-	TRNSYS ITT DELPHIN	-	TRNSYS ITT DELPHIN	
TUE	Netherlands	HAMLab	HAMLab HAMBase	-	HAMLab	HAMLab
TUW	Austria	ESP-r	HAM-VIE	-	BUILTOPT-VIE	
UCL	UK	EnergyPlus	EnergyPlus Canute_beta	-		
UG	Belgium	-	1DHAV + TRNSYS	-	TRNSYS	TRNSYS
ULR	France	-	TRNSYS SPARK	-	-	-

CE5: Most of the solutions introduced were only analytical or semi-analytical calculations, prepared without the use of any specific simulation tool.
CE6: Due to experimental schedule, no simulations were performed.

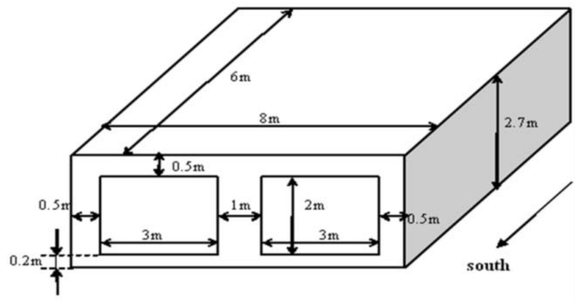

Figure 1. BESTEST base case building.

The results gathered comprised indoor air temperatures, heating and cooling loads (for cases 900 and 600) as well as solar radiation (incident radiation at all the walls and gains through the windows). Both detailed hourly values were collected as well as global results (annual loads, mean temperature, etc.).

All results clearly showed the differences between heavy- and lightweight structures. However, a spread of several degrees between different sets of results was obtained. The differences were mainly due to different modelling capabilities of the codes, and especially to the differences in calculating solar gains through windows. However it should be noted that the results concerning heating and cooling loads mostly corresponded well with the original range of results from BESTEST.

CE1 - Hygrothermal building simulation.

CE1 extended on CE0 by adding some analysis of the indoor and building envelope moisture conditions for the BESTEST building used in CE0. The original plan for CE1 was to add the moisture problem parts directly to the problem from CE0. For that purpose there was an internal moisture gain of 500 g/h from 9:00 - 17:00 every day. The air change rate was always 0.5 ach. The heating and cooling controls for all the non-isothermal cases kept the indoor temperature between 20 and 27ºC. The system was a purely convective air system and the thermostat was on air temperature.

Results from the original CE1. "CE1" was the original case of an exercise for simulations which include moisture exchange. It was posed with a relatively high degree of freedom for modelling a realistic building, based on the descriptions for thermal BESTEST cases. The results from different participants showed a very large spread. Big differences in results were coming from different assumptions that have been made on some of the input conditions both for energy and moisture modelling. The original case had too many uncertainties even within the thermal calculation, e.g. the presentation of the material data, window models etc. Facing the difficulty to interpret such data, it was decided to review the exercise giving much more details on the input data and on the way of modelling the problem.

This lead to some new variants of the Common Exercise: CE1A (an analytical case) and CE1B (a more "realistic", numerical case). The constructions, material data and solar gain were simplified.

Results from CE1A Analytical cases. This exercise applied the simplest conditions in terms of material properties and boundary conditions and used properties which facilitate the possibility to solve the case analytically (see Bednar and Hagentoft, 2005). Compared to the original CE1, the following changes were made: Constructions were supposed to be made of monolithic aerated concrete with constant/linear properties. Tight membranes on the outside, prevented loss of vapour from the building. The exposure was completely isothermal. The building had no windows. All models showed very good agreement with the analytical solution in this simple case, i.e.deviations were mostly less than 3% RH.

Results from CE1B "Realistic" cases. This exercise was the second part of the revised CE1: The constructions were still more simple than in the original CE1. All the envelope constructions were made of monolithic aerated concrete and faced outdoor air. There were no coatings or membranes on any sides, not even for the roof. Variations were run both for isothermal or non-isothermal conditions, and with or without solar gains in the building. Given the important spread between different numerical solutions, judging the results in terms of "correct" or "not correct" was very difficult. It was then preferred to go to Common Exercises 2 and 3 where measured data gave target solutions which could help to validate the models.

CE2 - Small climate chamber test

In order to design residential spaces for indoor humidity control, it is important to investigate the influence of ventilation rate and hygrothermal materials. The objective of this common exercise was to simulate conditions in a climate chamber at the Akita Prefectural University, Japan. A schematic view of the test room is shown in Figure 2. This test chamber was approximately half the size of a typical residential room. The internal volume of the test chamber was 4.60 m^3 and the area of interior surfaces 16.62 m^2. The walls, ceiling and floor of the test room consisted of 12.5 mm of gypsum board behind which was 100 mm of polystyrene (see Figure 2). In order to keep vapour- and airtight conditions in the chamber, an aluminium sheet was installed between the polystyrene and the gypsum board. The inlet and outlet for mechanical ventilation were located at the bottom and top of two opposite walls respectively. A small ventilation duct was connected to the outlet of the chamber to measure the ventilation rate accurately.

Two kinds of experiments were carried out. The first examined the influence of ventilation rate, while the second examined the influence of both the quantity and location of the hygrothermal materials within the chamber.

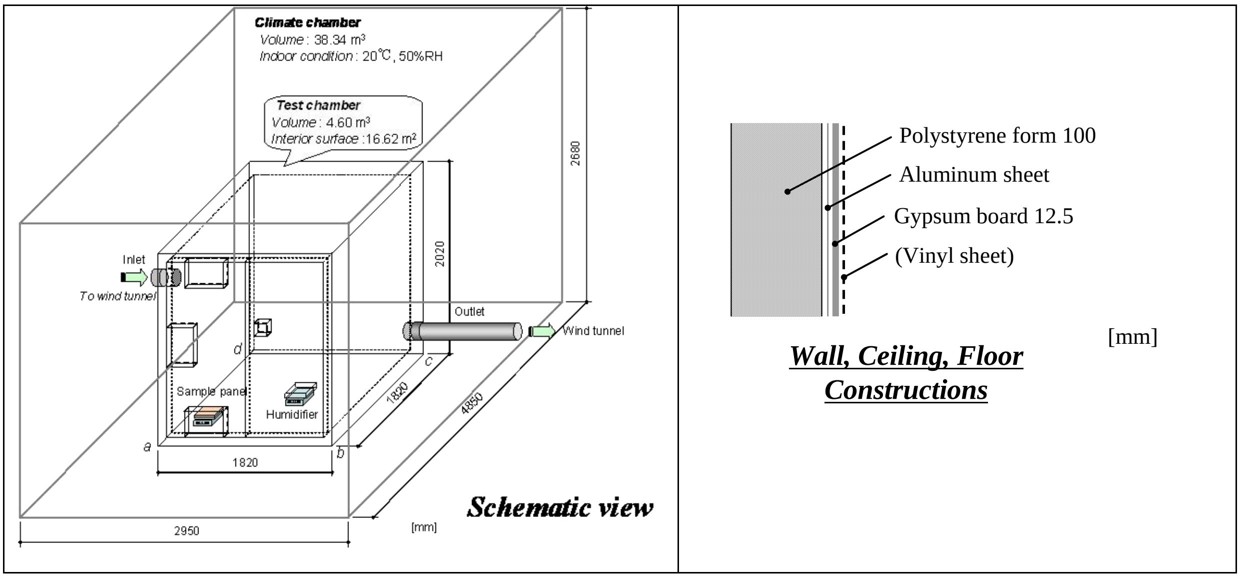

Figure 2. CE2: Schematic view of the test chamber and the construction.

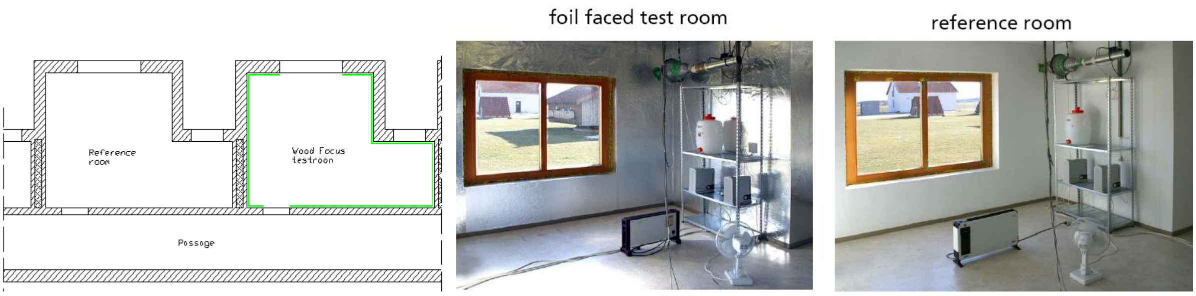

Figure 3. Experimental rooms used at the Fraunhofer Institut für Bauphysik, Germany, to generate field data for CE3. "Reference room": The surfaces of the walls and the ceiling are coated with common gypsum plaster and paint. "Test room": Surfaces of the walls and the ceiling are completely coated with aluminium foil.

*Experimental settings***.** Each experiment consisted of a preconditioning period followed by 6 hours of humidification and 12 hours without humidification, during which variations of indoor temperature and humidity within the small chamber were evaluated.

Humidification took place by evaporating moisture from a water reservoir that was heated by an electric heating element. The water reservoir was weighed by an electric balance. The target moisture production rate was about 20 g/h. Several experiments were performed varying the ventilation rate (none, low and high) and the surface of hygroscopic materials (none, one, three or five walls).

*Comparison between simulation and experimental results***.** In all the cases there was a rise of about 1.5-2°C in the air temperature, due to vapour production. It was correctly found by most of the models.

Experimental humidity data were higher than simulated values in all the cases. Moreover:

- Experimental values agreed well with simulated values in cases which focused on: High ventilation, one hygroscopic surface on the wall, and no hygroscopic surfaces.
- The simulation tools underestimated the peak absolute humidity by approximately 1g/kg in cases with: five hygroscopic surfaces, three hygroscopic surfaces on the wall, and one hygroscopic surface on the ceiling.
- The simulation tools underestimated the peak absolute humidity by approximately 2g/kg in cases with five hygroscopic surfaces and no ventilation, and one hygroscopic surface on the floor.

The agreement was better when the impact of moisture buffering was lower (high ventilation and no hygroscopic surfaces). The biggest differences occurred in cases with no ventilation and with hygroscopic surface on the floor. It may indicate that besides moisture adsorption on hygroscopic surfaces there was some stratification of the indoor air. Indeed, with no ventilation the air was very still in the test chamber, so there was no mixing. Moreover, water vapour is lighter than dry air, so it has a tendency to rise, which is a factor to be considered when the hygroscopic material is on the floor.

CE3 - Double outdoor climatic chamber test

The intention of this common exercise was to simulate two real rooms (called *test* and *reference*), which are located at the outdoor test site of the Fraunhofer Institute of Building Physics in Holzkirchen, Germany and are shown in Figure 3. Experiments were carried out during winter and spring period. In the *reference room* was used a standard type of gypsum board with a latex paint (equivalent diffusion layer thickness, s_d = 0.15 m). The walls and the ceiling of the *test room* were fully coated with aluminium foil; the test material (uncoated gypsum board) was attached to the walls and the floor of the room.

The experiments in both rooms were made for the following four steps:

1. *Test room with aluminium foil*. During the first test step no material was attached to the walls in the test room and measurements were run for a period of 17 days. This test showed the difference between the hygroscopic reference room and the test room with aluminium foil where there were no sorption effects.

2. Test room with gypsum board on the walls. In the second step, gypsum boards were attached on all wall surfaces. This experiment was run for a period of 35 days.

3. Test room with gypsum board on the walls and the ceiling. For this experiment, additional gypsum boards were installed on the floor (in total approximately 65 m²). The test was carried out for a period of 26 days.

4. With solar gains in the rooms. The influence of solar radiation through the windows was considered in Step 4, and additionally the indoor climate conditions were measured with and without heating system. The test room was empty and only covered with aluminium foil.

Output from the investigations. For each calculation hourly averaged air temperatures, relative humidity and the energy required to maintain the desired temperature were reported for each room. The results of the measurements showed the influence of different materials in comparison to the relative humidity in the rooms. Thirteen participants with different simulation tools took part in the exercise. All the models could calculate the indoor RH with an error of approximately 3% for the test room with no sorptive surfaces inside. But with gypsum boards, which have a good moisture buffering behaviour, most of the models had difficulties in calculating the indoor RH correctly. The results showed deviations up to approximately 20% RH between measurements and some simulations. However, for lower buffering capacity (painted plaster), the agreement with the measured results was better and the error decreased to maximum 8%. In Step 4 when the heating system was running and solar gains were considered the spread of the results was not too high. But for the results without a heating system, only one model simulated the indoor temperature in a correct way.

CE4 - Moisture management for reducing energy consumption

The intention of this common exercise was to show that an appropriate management of the indoor moisture conditions could reduce the building's energy consumption. The objective of the exercise was to use a relative humidity controlled (RHC) ventilation system combined with the effects of moisture buffering materials in order to reduce the energy consumption and improve the indoor climate.

The exercise was based on the two real test rooms which were used in CE3. The target relative humidity values of the indoor air were between 40 and 50%.

The participants were asked to perform five simulations changing ventilation system data and moisture buffering capacity of the envelope:

Run A: the original results from CE3, with constant ventilation

Run B: using original finishing materials and the RHC ventilation system,

Run C: using original finishing materials and a RHC ventilation system with maximum and minimum airflow values modified by the participants

Run D: using the RHC ventilation system from run B, but changing the moisture buffering capacity of materials by using different material properties and different surfaces.

Run E: combining both: the ventilation and the materials in order to reduce the energy consumption and improve indoor RH.

The simulations were run for a period from January to April covering cold and mild periods. 6 solutions were provided by 6 different participants. Even if some differences in results were noticed, an overall good agreement was found for the different simulations. It was found that RHC ventilation reduces the spread between the minimum and the maximum values of relative humidity. It was also found that the use of a RHC system could reduce the mean ventilation rate of about 30 to 40 % in the cold period and generate 12 to 17 % of energy savings. It should be stressed that the energy savings are done by keeping the peak RH values at the same level, therefore without raising the risk of condensation. However, during the mild period the savings were much lower (~2%), mainly because of higher moisture content outside. It was also confirmed by the results that the use of moisture buffering materials enables a significant reduction of the amplitude of daily moisture variations.

CE5 - Real life row house

With exercise 5, a practice-related case was introduced among the common exercises. The case concerns a low income estate of 48 two storey houses built in the 1970s (Figure 4). All had an un-insulated floor on grade, un-insulated cavity walls, double glazed aluminium windows on the ground floor, single glazed aluminium windows on the first floor and a f ceiling composed of (from inside to outside) (1) gypsum boards mounted with open joints, (2) 6 cm thick glass-fibre bats with a vapour retarder on the underside, (3) an un-vented air space and (4) corrugated fibre cement plates as roof cover (Figure 4, right). The two floors were linked by an open staircase in the living room. The dwellings were adventitiously ventilated, while purge ventilation was provided by opening windows.

85% of the dwellings showed traces of moisture on the cathedral ceiling, while a large number of the inhabitants complained about dripping moisture in the bedrooms after cold nights. A detailed inspection of some roofs revealed poor installation of the glass-fibre bats, abundant traces of condensation at the underside of the corrugated fibre-cement plates, mould on the rafters and traces of condensate at the back of the internal lining.

The suggested solution was: (1) renovate the roof to obtain a better solution; (2) upgrade the overall poor insulation quality of the dwellings; (3) equip the dwellings with a purpose designed ventilation system.

The exercise. The objective of the exercise was not comparing software-based solutions, but evaluating if the Annex 41 participants could solve an engineering problem using simplified approaches. For that reason, the exercise was kept as a steady state problem, based on a cold week.

The exercise was split in three successive steps:

- Step 1: ground floor and first floor heated, daily vapour release constant over the week, air leakage through the façade distributed proportionally over the surface
- Step 2: ground floor heated, first floor not heated, vapour release on both floors given on an hourly basis, air buffering only, air leakage through the façade distributed proportionally to the window perimeter lengths
- Step 3: as step 2 plus moisture buffering by the fabric included

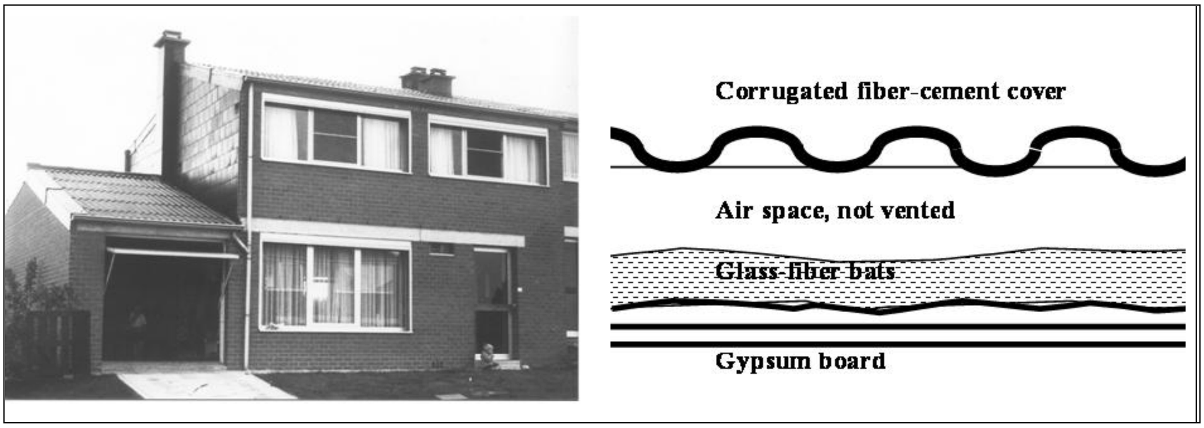

Figure 4. The dwelling considered in CE5.

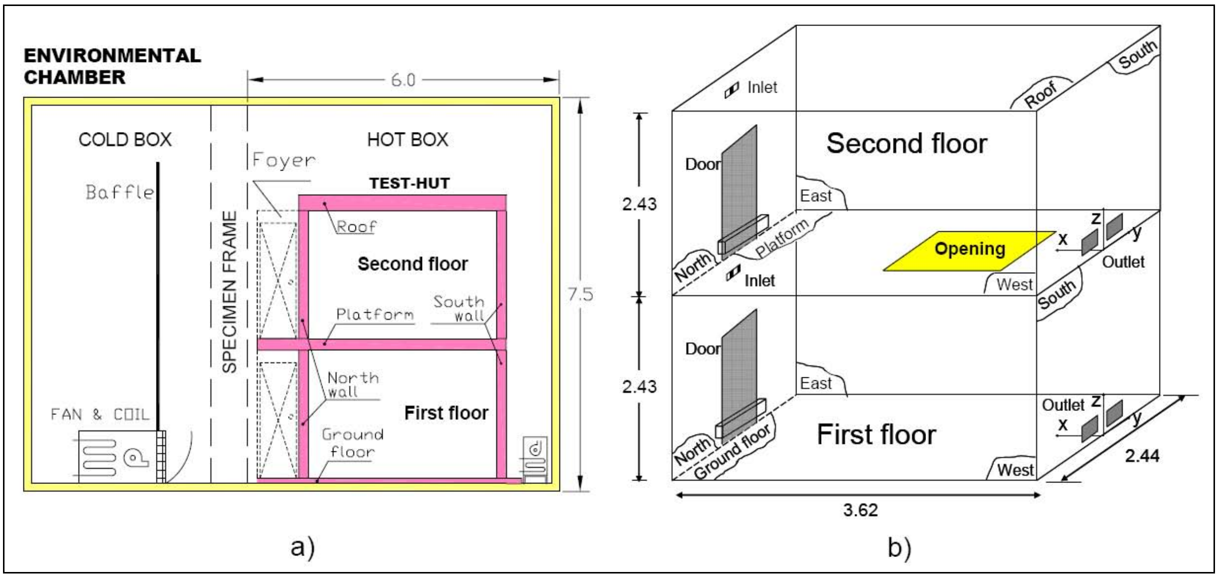

Figure 5. CE6: a) Schematic drawing of the two-story test-hut inside the Environmental Chamber. b) Interior dimensions of the two-story test-hut and name of the test-hut components (dimensions are in meters).

Conclusions from CE5. Most of the solutions introduced to CE5 were only analytical or semi-analytical calculations, prepared without the use of any specific simulation tool. The exercise proved that solving real life problems, using simplified methods, is not as simple as expected. One has to know a lot about what could happen before the calculations. The simple models used should be physically correct. Nodes for air balance calculations must be chosen carefully. Hand calculations of these balances are hard to perform as iteration is needed. Modelling in a spreadsheet programme anyhow can easily be done. The material or system property values used should be realistic. It is important to ensure that the mass balances for air and for vapour are kept – this was not always the case for the proposed solutions. Likewise, heat balances should be set up by correctly considering all the involved heat flows. And, finally, the results have indicated there could be some problems in basic interpretations, e.g. there might even have been some possible confusion of inside/outside dimensions.

CE6 - Two-story test-hut data from Environmental Chamber

The objective of the experimental study was to generate reliable datasets that will serve first to advance the understanding of the whole building response to heat, air, and moisture (HAM), and secondly to validate ongoing and future numerical models. For this objective, tests were carried out in a two-story test-hut that was assembled inside the Environmental Chamber at Concordia University (Canada).

In the first stage, the test rooms were isolated and the HAM transfer and moisture buffering parameters were monitored. Each room was tested independently to study the moisture buffering capacity of two finishing materials and furniture, and to study airborne moisture distribution within a room. These tests are referred herein as the “single room” tests. In the second stage, the upper and lower rooms were coupled by a horizontal opening to study the inter-zonal HAM transport through this opening and the resulting airborne moisture distribution in both rooms. These tests are referred herein as the “two-room” tests.

Environmental Chamber and test-hut construction The Environmental Chamber was used to provide the desired outdoor conditions (see Figure 5a). The temperature in this large chamber was controlled by two cooling systems and two electric heaters. A blower (5.7 m^3/s) and small portable fans provided the air circulation in the large chamber.

The test-hut consisted of two rooms with internal dimensions of 3.62m x 2.44m x 2.43m each (Figure 5b). The test-hut represents typical wood-framed construction of Canadian houses. In each floor, a small foyer was built adjacent to the north wall to reduce disturbance to the test rooms when doors were opened to set new conditions inside the rooms and to house part of the data acquisition system.

The east and west walls (see Figure 5b) were used to study the moisture buffering capacity of two different finishing materials, uncoated gypsum board and pine panelling. The rest of the indoor surfaces were covered with aluminium sheets to avoid any additional moisture buffering effect. For the non-hygroscopic cases, the east and west walls were covered with polyethylene sheets.

Materials used in this study were generic. Hygrothermal properties of similar materials were tested at IRC (NRCC). Also, surface mass transfer coefficients for uncoated gypsum board and pine panelling were measured at the University of Saskatchewan. Air leakage of the test-hut was measured at operating conditions. Air leakage varied from 0.014 to 0.044 h^{-1} for single room tests, and from 0.018 to 0.027 h^{-1} for two-room tests.

Conclusions from CE6. In total, 20 complete datasets that allow the study of the moisture buffering capacity of two finishing materials and furniture, airborne moisture distribution within the rooms and inter-zonal HAM transport through horizontal openings, were generated. They may be used to validate ongoing and future Whole Building HAM and CFD models. However, due to experimental schedule, no simulations were performed within Annex 41 on CE6.

SOME COMMON CONCLUSIONS

The Common Exercises have illustrated the complexity of whole building hygrothermal modelling. It was possible to find some consensus among solutions only for an extremely simple isothermal case: a monolithic building without windows and no contact with the ground (CE1A).

But the Common Exercises have stimulated some developments of different software as well as some original use of already existing programs. Mainly in CE0 some energy models were improved in more moisture oriented programs, and in CE1 moisture modelling was enhanced in more energy oriented tools. The improvement of the models was noticed in CE3, when the obtained agreement was much better that in CE1.

All common exercises showed that there is a need for some consensus data concerning heat and moisture properties of the materials, and more generally about all the input data. Same remark concerns the outputs: as energy and moisture are closely influenced by each other, some spread in relative humidity values can be easily explained by the spread in temperature values. Therefore, moisture content should be preferred over relative humidity for comparison purposes.

Also in such an integrated modelling, all elements are very important: For example some differences in the indoor relative humidity may be caused by the way solar gains and long wave radiation were modelled, and perhaps not so significantly by differences in the moisture model. Moreover, some participants stressed the importance of wall discretization. Differences are important for energy vs. moisture modelling; they can lead to numerical divergence.

A crucial question was raised during the discussion: how can we evaluate if the solutions are good or bad? This is especially important when there are no measured data. In such cases, could one say that the consensus solutions are good? The question remains open.

Globally the most encouraging results of all the Common Exercises are:

- Existing models have been “tested” for their suitability for the whole building hygrothermal simulation
- New models have been created, including upgrading and developing existing models to be able to handle also new aspects in “H”, “A” or “M”.
- Several existing computational tools were found to be able to deal with coupled heat, moisture and ventilation problems at the whole building level - they all gave similar results.

All exercises are described in detail in Woloszyn and Rode (2008). They can be used for validation of existing and future Whole-Building Heat-Air-Moisture simulation tools.

ACKNOWLEDGEMENTS

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